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Description

METHOD OF OPERATING A SATELLITE FOR END-OF-LIFE MANEUVERS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation-in-part of allowed US patent application 10/255,540, which is incorporated by reference herein.

BACKGROUND OF INVENTION

[0002] The present invention relates to a method for controlling the operation of a satellite and, more particularly, to a method for controlling the operation and consumption of propellant of a satellite near the end of its useful life.

[0003] Spacecraft propulsion systems typically use at least two tanks that store propellant therein. The propellant is used to maintain the satellite orbit due to various perturbations in space. A small amount of propellant is required to maintain an orbit. When a satellite nears the end of its propellant, the satellite may be placed in a graveyard orbit.

[0004] A standard method for determining the amount of remaining propellants on a spacecraft in orbit is to keep track of the propellant by bookkeeping. That is, keeping track of the burn times and thus deducing the amount of propellant used which can be subtracted from the propellant loaded prior to launch. This method is typically no more accurate than one percent of the loaded propellant. This amount may be equivalent to several months of station keeping. Because the spacecraft is deorbited several months before the end of its useful life, potentially millions of dollars in revenue are lost.

[0005] Another method for performing determining the amount of propellant is described in the parent application. The method described therein set forth a method that empties a tank. In some situations, it may not be desirable to empty a tank.

[0006] The present invention proposes a method that can be used on existing and future spacecraft to predict the amount of propellant therein without incorporating expensive fuel gauge type devices and without emptying a fuel tank.

SUMMARY OF INVENTION

[0007] The present invention provides a method for determining

an amount of propellant to be saved for end-of-life maneuvers so that the satellite can be controllably deorbited without shortening its regular useful life.

[0008] In one aspect of the invention, a method of operating a satellite comprises a method for operating a satellite so that a predetermined amount of propellant is left to perform end-of-life maneuvers. A first pressure differential is established between a first propellant tank and a second propellant tank by pressurizing the first tank from a pressurant source. Propellant is transferred from the first tank to the second tank. The second tank is used for orbit maintenance. The first tank is used for end-of-life maneuvers. Propellant may be transferred between the tanks using a latching process so that a predetermined amount of propellant may be transferred from a non-empty tank to a full tank.

[0009] One advantage of the invention is that the present method may be used both on existing satellites and future satellites. By utilizing the present invention the end-of-life of the satellite is known to within days rather than months. Thus, any remaining station keeping and deorbit maneuvers with the banked (transferred) propellant may be confidently performed. It should be also noted that the

present invention applies to both three axis and spin stabilized spacecraft and can be applied to both mono-propellant and bi-propellant propulsion systems. Another advantage of the invention is that the pressurant source may be used to maintain a sufficient pressure of the propellant at the nozzles of the spacecraft. Yet another advantage of the invention is that emptying a fuel tank is not required. This allows the method to be performed at a more convenient time.

[0010] Other aspects and advantages of the present invention will become apparent upon the following detailed description and appended claims, and upon reference to the accompanying drawings.

Brief Description of Drawings

[0011] Figure 1 is a perspective view of a spin stabilized satellite having the control system according to the present invention.

[0012] Figure 2 is a perspective view of a three axis satellite according to the present invention.

[0013] Figure 3 is a diagram of a satellite in geosynchronous orbit with canted radial and axial thrusters to adjust the satellite's position.

[0014] Figure 4 is a simplified diagrammatic view of a propellant

thruster control system according to the present invention.

[0015] Figure 5 is a block diagram of a first method for operating a satellite according to the present invention.

[0016] Figure 6 is a flow chart of a second embodiment of operating a satellite according to the present invention.

[0017] Figure 7 is a flow chart of a third embodiment operating a satellite according to the present invention.

DETAILED DESCRIPTION

[0018] In the following figures the same reference numerals will be used to identify the same components. The present invention may be applied to various types of satellites including spin stabilized and three axis satellites as well as satellites in any orbit. Also, the present invention is applicable to both mono-propellant and bi-propellant systems. Further, the present invention is described with respect to two propellant tanks. However, the present invention may be adapted easily for spacecraft having more than two tanks.

[0019] The present invention utilizes a banked amount of propellant that is stored for end-of-life (EOL) maneuvers. Generally, the amount stored for EOL maneuvers may be determined in two ways. First, by controlling latching of

valves between the two tanks or, second, by equalizing the amount of propellant in the two tanks and thus calculating the amount in a first tank after the amount of propellant in the second tank is burned.

[0020] Referring now to Figure 1, a spin stabilized satellite 10 has a substantially cylindrical body 12 that is spun about a cylindrical axis 14 for stabilization in orbit. Radial thrusters 14 are positioned on the side surface 16 of cylindrical body 12. Typically, two sets of thrusters pointing in opposite directions are utilized. The side surface of the cylindrical body 12 has cutouts 18 through solar panels 20 to allow the thrusters 14 to protrude therethrough. The rate of spinning is controlled by firing the radial thrusters 14.

[0021] Axial thrusters 22 may also be included on the satellite 10. Axial thrusters 22 are fired to control the attitude or orientation of the satellite by adjusting the orientation of its spin axis 14. Canted radial thrusters 24 may also be included on satellite 10. Canted radial thrusters 24 provide spin stabilization. Apogee thrusters 26 may also be provided. Apogee thrusters 26 are used to lift the satellite up from a transfer over to a geosynchronous orbit.

[0022] A thruster control system 28 is coupled to a the thrusters

14, 22, 24, and 26. Control system 28 as will be further described below may be used to save a predetermined amount of propellant for EOL maneuvers. Control system 28 includes various components including the tanks for storage of the propellant.

[0023] Referring now to Figure 2, a three axis satellite 34 having a satellite body 36 is illustrated. Satellite body 36 is generally cubicle with six planar surfaces. Two opposite surfaces 38 have two east/west thrusters 40 to adjust the longitude of the satellite in geosynchronous orbit. Another pair of opposite surfaces 42 each have four north/south thrusters 44 positioned near the corners of each surface to adjust the latitude or inclination of the satellite. One of the remaining surfaces 46 has four axial thrusters 48 to control the attitude of the satellite by firing one or more of the thrusters. An apogee thruster 50 is positioned at the center of the surface 46 to propel the satellite from a transfer orbit to a geosynchronous orbit. After the satellite is transferred to the geosynchronous orbit, apogee thruster 50 is disabled.

[0024] Referring now to Figure 3, a spin stabilized satellite 10 is illustrated in a geosynchronous orbit 52 around earth 54. The orbit is directly above the equator 56 of earth 54. The

north pole of earth 54 is shown as arrow N. To illustrate the longitudinal (east/west) positioning of the satellite by its canted radial thrusters, only two thrusters 58 and 60 are positioned for propelling the satellite to the east and west, respectively. The inclination (north/south) of the satellite 10 can be adjusted by axial or apogee thrusters 62. At the end of its useful life, satellite 10 may be deorbited to vacate its position in geosynchronous orbit 52. Future satellites may thus be placed in its place.

[0025] Referring now to Figure 4, control system 28 is illustrated in further detail. Control system 28 is shown with a generic thruster 68. Thruster 68 may represent one or a number of the thrusters mentioned in Figures 1, 2 or 3. Thruster 68 receives propellant through a main feed tube 70. Secondary tubes 72 are fluidically coupled to main tube 70. Secondary tubes 72 are coupled to a first propellant storage tank 74 and a second propellant storage tank 76. Various controllable latch valves 78A, 78B, and 78C may be disposed within main feed tubes 70 and secondary feed tubes 72 to control the release of propellant. A controller 80 that is preferably microprocessor-based is included within control system 28. Controller 80 may be coupled to a satellite receiver 82 which in turn is coupled

to a receiving antenna 84. Controller 80 acts according to preprogrammed sequences and in response to commands received through antenna 84 and receiver 82. Thus, the controller is programmed to execute a number of steps as will be described below.

[0026] Controller 80 may be coupled to latch valve 78A, 78B, and 78C. Thus, controller 80 may control the operation, i.e., the opening and closing of the latch valves. Various types of latch valves are known to those skilled in the art. Preferably, the opening and closing of the latch valves may be timed by a timer 86 that may be integral to controller 80.

[0027] Controller 80 may also be coupled to heaters 88. Controller 80 can control the operation of heaters 88 to increase the pressure within tank 74, 76. Various types of heaters would be evident to those skilled in the art.

[0028] Controller 80 may also be coupled to pressured transducers 90 that generate pressure signals corresponding to the pressure in their respective propellant tanks.

[0029] Each propellant storage tank 74, 76 may be coupled to a pressurant source 92. A first valve 94 may be coupled to controller 80. Controller 80 is used to control the opening and closing of valve 94. Likewise, a valve 96 is coupled to

tank 74. A second valve 98 is coupled to tank 76. Valves 96 and 98 are also coupled to controller 80. As those skilled in the art will recognize, valve 94 is a redundant valve for the system and adds extra safety to the system. By controlling valves 94, 96 and 98, pressurant source gas from pressurant source 92 may be used to pressurize tanks 74 or 76. A pressure regulator (not shown) may be coupled in the area of valves 96 or 98. This may allow the amount of pressure to be controlled by controller 80. Of course, those skilled in the art will recognize that an amount of pressure to be provided may be controlled by the amount of the valve opening.

[0030] Referring now to Figure 5, the first of three embodiments of the present invention is described in further detail. In step 102, the first tank is emptied by burning to completion all the propellant therein. By controlling the latches, a pressure difference may be established between the first tank and second tank in step 104. In step 106, a precise amount of propellant is transferred from the second tank to the first tank that was previously emptied in step 102. A precise amount may be established by timing the opening and closing of the latch valves and thus controlling the flow through manifolds between the tanks. Transfer may

be directly observable by the pressure in both tanks being measured by the pressure transducers. The amount of remaining propellant may be determined by the controller and communicated to the ground or may be calculated on the ground. In one step 108 the portion of the second tank remaining may be used for orbit maintenance. In step 110, the first tank may then be used for EOL maneuvers. Because the amount is precisely known, the amount of EOL maneuvers that can be performed is also precisely known. This embodiment may be used for mono-propellant and bi-propellant systems. Typically, more than one tank is provided for each propellant in a bi-propellant system and thus the present invention may be performed on each one of the types of propellants.

[0031] Referring now to Figure 6, a second embodiment of the present invention is illustrated. This embodiment is particularly suitable for spinning spacecraft. Instead of emptying a propellant tank as described in the first embodiment, a pressure difference is established between the first and second tanks in step 112 by using propellant from the second tank. By opening latch valves between the tanks, the tanks tend to equalize. Propellant is transferred from the first tank to the second tank in response

to the pressure difference. Thus, in step 116 the pressure is equalized between the first and second tanks. This implies that the same amount of propellant is in each of the tanks. The equalization process is assisted by the rotational movement of the spacecraft. Of course, this assumes that the spacecraft is balanced when dry and that initial gas pressures in both tanks were equal at loading. The transfer is enabled by opening latch valves between the tanks until the pressures, as read by the pressure transducers, are the same. Of course, pressure equalization may be inferred without pressure transducers after a predetermined amount of time. In step 118 the propellant in one tank is used for orbit maintenance until the tank is empty. In step 120 the amount in the first tank may be inferred from the amount used in the second tank. Knowing the burn times and durations of the propellant from the second tank, the amount of propellant in the first tank is thus known. That is, because each of the tanks had an equal amount of propellant to start, the amount in the closed first tank is known. In step 122 the amount of propellant in the first tank may then be used for EOL maneuvers.

[0032] Referring now to Figure 7, a third embodiment of the

present invention is described in further detail. In step 130 the first tank is pressurized with the pressurant gas from pressurant source 92. Thus, controller opens valve 94 and valve 96 to allow the pressurant gas within the tank. Preferably, latch valve 78A is also closed during pressurization. Thus, in step 132 a pressure difference between the first tank and the second tank is established. In step 134 a precise amount of propellant is transferred from the first tank to the second tank by timing the opening and closing of latch valve 78A and 78B. At this point, valves 94 and 96 may be closed prior to the opening of latch valve 78A and 78B. The transfer may be directly observable by the pressure in both tanks being measured by the pressure transducers 90. In step 136 the amount in the first tank is burned to depletion. The first tank may then be vented in step 138. Step 138 is an optional step. In step 140, propellant in the second tank is transferred to the first tank. This equalizes the pressure in the two tanks. In step 142 the first tank may be pressurized using the pressurant source. In step 144 the amount in each tank is determined. The amount in each tank may be determined using the ideal gas law, flow rate modeling or a combination of the two. That is, by knowing the charac-

teristics, pressures, temperatures, diameters of the openings and tubes, the amount of propellant in each of the tanks may be determined. In step 146 the second tank may be used for orbit maintenance while in step 148 the first tank may be used for EOL maneuvers. The above use of a pressurant source is particularly useful in a three axis satellite. However, such a system may be used for a spinning satellite. It should be noted that this procedure may be done simultaneously for oxidizer tanks as well.

[0033] Because more propellant than that required for EOL maneuvers may be remaining in the first tank, the process may be repeated to reduce the amount in the first tank. Also, a similar process to that described in the first embodiment with respect to Figure 5 may be performed to reduce the amount of propellant in the first tank. The system and method of the present invention may be used for bi-propellant systems. That is, an amount of each propellant may be stored using the method described above. The propellant in a bi-propellant system may be propellant in at least two tanks and oxidizer in at least two tanks.

[0034] While the invention has been described in connection with one or more embodiments, it should be understood that

the invention is not limited to those embodiments. On the contrary, the invention is intended to cover all alternatives, modifications, and equivalents, as may be included within the spirit and scope of the appended claims.